Kufa Journal of Engineering
Vol. 15, No. 3, July 2024, P.P. 186-212
Article history: Received 20 March 2024, last revised 9 May 2024, accepted 13 May 2024

A ROBUST OPTIMISATION-EFFICIENCY-DECISION SCHEME FOR ELECTROHYDRAULIC FORMING USING HYBRID TAGUCHI-DATA ENVELOPMENT ANALYSIS-PARETO METHOD FOR ALUMINIUM ALLOY 1100 SHEETS IN AUTOMOTIVE PANELS

Olusola Michael Adeyemi[1], Boluvar Lathashankar[2], John Rajan[3], Swaminathan Jose[4], and Sunday Ayoola Oke[1,*]

[1] Department of Mechanical Engineering, University of Lagos, Lagos, Nigeria

[2]Department of Industrial Engineering and Management, Siddaganga Institute of Technology, Tumkur-572103, Karnataka, India

[3]Department of Manufacturing Engineering, School of Mechanical Engineering, Vellore Institute of Technology, Vellore, India

[4]School of Mechanical Engineering, Vellore Institute of Technology, Vellore, India

***Corresponding author: sa_oke@yahoo.com**

https://doi.org/10.30572/2018/KJE/150311

ABSTRACT

This paper proposes a hybrid T-DEA-P (Taguchi-Data Envelopment Analysis-Pareto) method to optimise and rank parameters of the electrohydraulic forming process using the aluminium (AA1100) sheets for automotive panel application. A linear programming model was formulated based on the integrated Taguchi – DEA data and solved using DEA software. The design variables are the stand-off distance, electrode gap voltage and medium. The constraints are formulated according to the levels specified in the level-factor table. Using literature data, the validation of the method was made. An important result shows that case 1 has the optimal parametric setting is SOD3E2V2M2. This is interpreted as a stand-off distance of 3mm, an electrode gap of 30mm a voltage of 260 volts and the medium as Oil with a viscosity of 0.89cP. The delta values are 16.026, 16.0605, 17.1109 and 37.3587. Delta values measure the rate of change of the average signal-to-noise ratios relative to the changes in levels. Based on the Pareto intervention, the medium is ranked first while voltage, electrode gap and stand-off distance are ranked second, third and fourth, respectively. The method aids in the planning activity for the forming process.

KEYWORDS

Parameter, setting, optimisation, forming, process, aluminium.

1. INTRODUCTION

The electrohydraulic forming (EHF) process, which emerged some decades ago as a substitute for the conventional forming method is still relevant nowadays (Zhang et al., 2020; Zavari et al., 2020; Dai et al., 2022). The EHF process is an effective route to forming and material transformation (Holzmüller et al., 2023; Wang et al., 2023). Moreover, as competition within the manufacturing industry increases, product complexity and the demand for formed products are heightened (Hvam et al., 2020; Budiono et al., 2021). Then, the optimisation of process parameters in the EHF system is enabled for superior value-adding optimal performance instead of sub-optimal levels (Zohoor and Mousavi, 2018; Ahmed et al., 2020). This is associated with minimizing waste, maximizing productivity and profit and other issues (Avrillaud et al., 2021). The present study is significant because it tackles performance issues of the negative influence of the use of poor-performing data for decision-making in the electrohydraulic process (Kosenkov and Bychkov, 2019; Natarajan et al., 2021; Panwar et al., 2024). Furthermore, this study analyzes the optimisation and ranking characteristics of the EHF process with an emphasis on aluminium (AA1100) sheet automobile panels. This is because as a result of the changing manpower structure, dwindling training of workers in the mechanical industry and the unusual economic misfortune of industries, optimisation has been studied and appropriate change in the forming process has been considered (Zohoor and Mousavi, 2018; Ahmed et al., 2020).

However, activities in the present-day EHF process are still sub-optimally operated in many situations (Elangovan and Narayanan, 2010; Ahmed et al., 2020). To tackle this problem, the Taguchi method has been implemented, which provides an economy of experimentation (Balasundar, 2013; Lakshmi et al., 2022). Though popular in usage within the forming arena, the traditional Taguchi method has been criticised for having little control over the parameters when discrimination is sought and there is a sense of focusing on the important parameters for the forming process (Lakshmi et al., 2022). Therefore, the Taguchi method has been recently favoured because it has a driving mechanism for both optimisation and ranking at the same time (Ayaz et al., 2013; Shrivastava et al., 2019; Modi and Kumar, 2019).

Notwithstanding, while the platform of data envelopment analysis (DEA) provides efficiency measures, the inability of process managers to obtain information from the combination of optimisation, efficiency and parametric discrimination is a handicap situation in decision-making (Grynia et al., 2024; Wu et al., 2024). It prompts the use of Pareto analysis, Taguchi method and DEA to solve the problem. To the best of the present authors' knowledge, the extant literature has failed to recognize a method to minimize, maximize or achieve a target value in the EHF process while optimising with the Taguchi method and ranking the output with the Pareto analysis, evaluating the efficiency of the process using the decision making unit concept of DEA.

Although numerical analysis on the electrohydraulic process for enhancing the insight of the process engineers has gained researchers' attention, and policymakers' interest and has attracted decision-makers for some years now, the idea of developing and applying decision-enhancing tools for optimisation studies is sparsely noticed in the literature (Yu et al., 2017; Zavari et al., 2020; Zheng and Yu, 2021). Worse, there is no comprehensive approach to optimising the variables of the electrohydraulic process in a fast and understandable manner through the economy of experimentation and still measuring the system's efficiency (Pérez et al., 2019; Li et al., 2023). To bridge this gap, this article deploys the T-DEA-P method comprehensively and understandably to achieve the goal of the EHF process. Thus, to overcome the limitations arising from the use of previous studies, the present study proposes a robust T-DEA-P as a foundation to establish the optimisation values of the parameters at the Taguchi method. Efficiency measurements are conducted using the DEA while the experimental and parametric discrimination is achieved using the Pareto method. Once the values are obtained, they could be used to set standards for the various parameters and possible attainment levels. To our knowledge, our article showcases the first application of this robust model in the EHF process domain.

Moreover, the high number of publications adopting the Taguchi method in all aspects of engineering research indicates high interest and confidence in the method. This is partly responsible for the growth of research on forming and the performance improvement in forming in the past few years. But growing along with research interest in Taguchi is the research gap, which shows the limitation of researchers to the traditional use of orthogonal arrays, translation of these arrays into actual values and computing the signal-to-noise ratios. Then the response table is developed to provide information on the optimal parametric settings, delta values and the ranks of the EHF parameters, for instance. This gap in knowledge impacts negatively on decision-making by the process engineers. However, engineers under/overestimate the number of parametric values. Besides, the time to implement the forming process has been inadequately predicted. This unfortunate consequence of this situation has many aspects. First, the confidence in using the Taguchi method has ended in some engineers in practice as well as researchers. This deters the potential of the Taguchi method in bridging the gap, and concurrently solving the efficiency evaluation problem, the present investigators have decided to provide a fresh insight into the Taguchi methodical analysis to promote the interest of forming engineers and researchers. Thus, in this article, the Taguchi method has transferred into a hybrid method consisting of the Taguchi method, DEA and the Pareto method, which has the attributes of optimisation, efficiency and decision-making. This will help the practising engineer to concurrently optimise the EHF process, measure the efficiency of the associated parameters and streamline them to the essentials for the focus on the goal of the process.

2. LITERATURE REVIEW

EHF has been defined as a process principally used for the production of small items in high volumes (Dai et al., 2022). These items, for instance in automobile parts, have complex shapes. Where electrical energy is sufficient, it is often taken advantage of by converting it to the production of pressure waves having a steep front. Other applications are bell housings, manifolds, sensor covers and gas tanks. In this section, a review of the literature was conducted using the databases of ScienceDirect, Sage and the Google search engine. The keywords introduced in the searches are electrohydraulic forming, Taguchi method, optimisation and ranking. Next is the discussion of the articles reviewed. Based on the research momentum generated by earlier researchers, EHF process studies progressed as (Homberg et al., 2010) worked on energy utilization during the forming process. It was concluded that smaller radii are obtained as energy discharge increases. In 2012, (Bonnen et al., 2012) focused on aluminium panels, which is the subject of the present authors. They concluded that the pulsed electrohydraulic process is a superior approach to the alternative traditional method. A follow-up study was made by (Bonnen et al., 2013) with a conclusion that erosion is not influenced by the entrained air that it happens at the first stage according to the numerical simulation results obtained.

In 2014 and 2015, interest in exploring energy generation during the EHF process was revealed by (Homberg et al., 2014) and (Jenab et al., 2015), respectively. The first set of researchers analysed the influence of input parameters (i.e. lever of kinetic energy and working media height among others on the reliability as well as reproducibility of the EHF and neuromechanical process. (Jenab et al., 2015) concluded that the formability of aluminium (AA5782-0) material enhanced on reaching an energy threshold of 8-10kJ.

In 2017, the studies by (Yu et al., 2017) and (Ahmed et al., 2017) are noteworthy. In the first study, the authors compared the physical appearance (notably the die capacity, working hardness and wall thickness) of the outputs from the forming process with those of electromagnetic forming. They concluded that superior performance was demonstrated by the EHF process compared with electromagnetic forming. However, the focus of

(Ahmed et al., 2017) was to establish the ability of aluminium (AA5052) sheets when tested using two methods: the conventional method and the EHF method. They concluded that a growth of 40% in strain limit was observed in the EHF method over the conventional method. The above studies have shown interest in several aspects of the EHF process, notably an effectiveness study, shape formation and energy expenditure during the forming process. Additional studies are further reviewed as follows.

In 2018, a simulation study was conducted by (Sarraf and Green, 2018) by applying the Rousselier damage model while the material used is the DP600 label. In two studies occurring in 2019, (Pérez et al., 2019) established an association between the electric charge from the forming process and the pressure field parameter. They concluded that the high voltage of the electrohydraulic system is not the same as the laboratory experiment. Then, (Kosenkov and Bychkov, 2019) simulated the influence of step form on the efficiency of the EHF process. It was concluded that the maximum efficiency exists on using the conical shape as the discharge chamber. However, more intensive studies have been reported in the year 2020 to date as the rate of publication has grown. In 2020, (Zhang et al., 2020) and (Zavari et al., 2020) analysed the characteristics of metals by the flexible-die component of the EHF process. A further growth in the number of published reports was noticed in 2021 with four studies captured in the present literature review, as follows: (Zheng and Yu, 2021) experimented with the impact of the scoreboard while deforming the DP600 sheet in the EHF process. (Wei et al., 2021) differentiated between the numerical results and experimental outcomes using the tubular analysis idea on the aluminium (AA6061) material in the EHF process. (Cai et al., 2021) reported that growth in the discharge voltage of joint stainless steel narrow-walled pipe and aluminium (AA6063) material caused a corresponding growth in the deformation level. (Zhang et al., 2022) enhanced the material flow to minimize busting and bulging tubes. (Dai et al., 2022) used a modified Lurge friction model to control the electrohydraulic system subjected to light loads.

Most recently, in 2023, four studies were captured: (Zhang et al., 2023), (Li et al., 2023), (Wang et al., 2023) and (Holzmüller et al., 2023). The first study used the characteristics of the stepped discharge methods of electrohydraulic shockwaves to analyse the EHF system experimentally. They found that the breaking tank for the sample, electric energy and impact times are less in the stepped modes. (Li et al., 2023) controlled the multiple electrohydraulic systems using the terminal sliding observer. They concluded that the observer was effective when simulated values and experimental results from it were studied and compared. (Wang et al., 2023) focused on the antisymmetric characteristics of metals within the EHF process of the eccentric and explosive types. It was concluded that eccentric behaviour often develops with this system. (Holzmüller et al., 2023) experimented with the aluminium sheet to compare the formability of the electromagnetic and EHF processes. It was concluded that if the distance between the blank and coil is high, more effects on the electromagnetic forming process are felt than on the EHF method.

Based on these revealed gaps in knowledge on the EHF process, this study proposes an approach to assess the optimisation performance of the aluminium (AA1100) sheets for automotive panels. Compared with previous research, the innovation of this research is observed in these aspects: (1) a Pareto index is built on the Taguchi method that promotes the economy of experimentation and productivity gains as the process engineer focuses on the most critical parameters for decision making based on the 80/20 rule. (2) Based on the examination of the aluminium (AA1100) automobile panel in forming process, optimisation and ranking decision suggestions are proposed (3) The coincidence analytical capability of the DEA comprehensively assesses the aluminium (AA1100) automotive panel forming process parameters. It establishes causal inferences where the independent real influences of the parameters in the EHF process are known. Thus it produces ranks, delta values and optimal parametric settings that yield more robust scientific assessment outcomes.

The findings of this research provide both theoretical and practical significance. From the theoretical viewpoint, the optimisation assessment schemes comprising the Taguchi-Pareto and the grey wolf algorithm are developed, establishing the association between the signals in quantity and speed, noise and the response of these composite features of the model in providing the theoretical and methodological foundation for towering-quantity forming performance. From the practical viewpoint data and study conclusions support the forming process manager and offer innovative thoughts to promote high-level forming performance technically and in managerial decisions. The results of the study then offer useful inputs for forming programme planning.

3. METHODS

The methodology adopted in the present work is the integration of the Taguchi method with the DEA and the Pareto method. Thus, the proposed T-DEA-P approach utilized in the present study is explained in the following steps:

Step 1: Pre-processing data analysis: Here, the authors need to define the major inputs and outputs of the system being analyzed. In this article, this step had already been conducted in the reference article used, where the experimental data is extracted for the present study for the validation of our T-DEA-P method. Thus, data was gathered from a paper by Shrivastava et al.

(2019). The inputs are defined as the standoff distance, electrode gap, voltage and medium. However, two categories of outputs are defined, which are the peak major strain and the done height, the process which they represent is called the EHF process. The specific example product analyzed is the aluminium (AA1100) sheets and the application is for the automobile panels.

Step 2: Define the number of parameters and their levels: Having established four parameters for the present study from the reference study, the levels are also stated. However, in the new study the level can be established by collecting a set of data points, say 20 data points. These are then arranged in the order of increasing values (i.e. ascending order). They are afterwards calculated based on the averages of each group. Thus, each group will have a representative value, which will be considered as the level of that data set. If five groups are made, then there will be five levels.

Step 3: Install an orthogonal array: based on the combination of the factors (parameters) and levels, an orthogonal array is installed with the help of any experimental design software. In the present situation, Minitab 16 (2020) is used to generate the orthogonal arrays.

Step 4: Define the criterion of the signal-to-noise ratios: Here three major criteria are used. The first is the higher-the-better criterion. The second and the third ones are the lower and best, respectively.

The smaller-the-better is shown in Equation (1), larger-the-better in Equation (2) and nominal-the-best in Equation (3) (Oji and Oke, 2020).

$$\text{S/N} = -10 \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

$$\text{S/N} = -10 \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right) \tag{2}$$

$$\text{S/N} = -10 \log_{10} y_i^2 / s^2 \tag{3}$$

where y_i is the performance characteristic of the i^{th} observed value

n is the trial number

s^2 is the variance of observations

Step 5: Compute the signal-to-noise ratios. A spreadsheet could be used for this purpose and MS Excel has been used for evaluation in this instance.

Step 6: Delta value, optimal parametric setting and ranking were determined. Delta values measure the rate of change of the average signal-to-noise ratios relative to the changes in levels.

It aids in simulating and understanding which way the signal-to-noise ratios will more when varying the number of levels at which the measurement of the parameters is taken. Optimal parametric settings reveal the maximum value (i.e. for a larger-the-better criterion) or minimum value (i.e. for a smaller-the-better criterion) possible for each system parameter by considering the system boundaries without violating the constraints. Furthermore, Moreover, each rank of the parameters signifies how the average signal-to-noise ratios of the electrohydraulic forming data are compared by parameters.

Step 7: Decision-making unit equations were generated and three different sets of objective functions and constraints were established. While formulating the linear programme, several cases may emerge, which are options for the consideration of the best. Solve each of these options and consider the best.

Step 8: The first set of objective functions and constraints, which represent the weights was multiplied by the translated orthogonal array data

Step 9: Signal to noise ratio was calculated for the new set of data.

Step 10: Based on the arrangement of experimental trials and the associated SNRs, obtain a cumulative percentage of the SNR. Notice that first, the absolute SNRs may be calculated. Then the proportion of each SNR out of the total is computed. The absolute of the signal-to-noise ratios result was computed and the sum was done, which led to the cumulative percentage calculation.

Step 11: Apply the Pareto principle to the computed percentage cumulative frequency on an 80% limit. Values above 80% were discarded. In practice, an exact 80% may not be attained so the SNR which is the closest to this value is chosen.

Step 12: Delta value, optimum parametric setting and ranking were performed using the new sets of data.

Step 13: Steps 9-12 were repeated but with the second set of objectives and constraints obtained from the decision-making unit equation.

4. RESULTS AND DISCUSSION

4.1. Taguchi method

To implement the Taguchi method, the three principal tasks conducted are firstly the establishment of the quality attribute and the choice of the parameter for the assessment. Here the present authors studied the EHF literature to establish the most important parameter to represent the process such that when they are improved, the changes are evident and would be reflected in the performance of the EHF process. These four parameters from a large number of possible ones were used to represent the studied EHF process. These are the voltage, stand-off distance, electrode gap and medium. The data regarding this was taken from (Shrivastava et al., 2019) (see Table 1).

Table 1. Control factors and their levels (Shrivastava et al., 2019)

Control factor	The symbol for coded value	Number of Levels		
		1	2	3
Stand-off distance	A	10mm	20mm	30mm
Electrode gap	B	20mm	30mm	40mm
Voltage	C	220V	260V	300V
Medium	D	Water (0.89cP*)	Oil (1.53cP **)	Air (0.01837***)

Key: *,** and *** are modified values according to the present authors

By systematically varying the controlled parameter and analyzing the resulting response variables, the aim is to identify the optimal settings for the EHF process. The second important task in this section is to choose the adequate orthogonal array with which the designed parameters are to be assigned. For the determination of the orthogonal array, an L9 framework involving 9 rows was used since the number of experiments generated was desired to be minimized for computational ease. Each EHF parameter is linked to each experimental trial, Table 2.

Table 2. Parameters and signal-to-noise ratios

Orthogonal array					Translated orthogonal array				
Sr. No.	SOD (mm)	Electrode gap (mm)	Voltage	Medium	SOD (mm)	Electrode gap (mm)	Voltage	Medium	SNR
1	1	1	1	1	10	20	220	(0.89 cP) Water	4.9655
2	1	2	2	2	10	30	260	(1.53 cP) Oil	9.6028
3	1	3	3	3	10	40	300	(0.01837 cP) Air	-28.6972
4	2	1	2	3	20	20	260	(0.01837 cP) Air	-27.6887
5	2	2	3	1	20	30	300	(0.89 cP) Water	2.5332
6	2	3	1	2	20	40	220	(1.53 cP) Oil	3.3763
7	3	1	3	2	30	20	300	(1.53 cP) Oil	3.0380
8	3	2	1	3	30	30	220	(0.01837 cP) Air	-27.6879
9	3	3	2	1	30	40	260	(0.89 cP) Water	2.8461

The third task is to analyze the experiment using the SN ratio. The S/N ratio is the signal-to-noise ratio, which measures the desirable signals of the EHF process and compares them with the undesirable noise from the same system. The aim is to achieve the best performance of the system when the signal-to-noise ratio is the highest. Furthermore, the signal-to-noise is obtained from Equation (2) in the section on methodology. To apply this equation the focus of each computation will be on each experimental trial. Consider experimental trial one for Table2. Table 2 shows the parameter, namely SOD, electrode gap, voltages and medium. The parameters are the most important ones in measurement exercised on the EHF process. However, based on the higher-the-better signal-to-noise ratio, the second to the last column in

Table 2 is computed. Then the mean is obtained in the last column. To display the higher the signal-to-noise ratio, the value under each of the four parameters should be considered. The first is the reciprocal of the squares. In this case, 1/100, 1/400, 1/48400 and 1/0.7921 are obtained for the respective parameters of SOD, electrode gap, voltage and medium. Furthermore, these values are summed up to obtain 1.2750. Furthermore, this result is divided by 4 to obtain 0.3187. However, the logarithm of the value is to be obtained as -0.4966. Finally, this value is multiplied by -10 to obtain 4.9655. This mentioned computation is for experimental trial 1. However, for experimental trials 2 to 9, -28.6972 to 9.6028 are obtained as the range of values. The next stage of the analysis is to compute the average signal-to-noise ratio, Table 3.

Table 3. Response table

	Factors (parameters)			
Level	**SOD (mm)**	**Electrode gap (mm)**	**Voltage**	**Medium**
1	-4.70963*	-6.56173	-6.4487	3.448267
2	-7.25973	-5.18397*	-5.07993*	5.339033*
3	-7.26793	-7.4916	-7.70867	-28.0246
Delta	2.5583	2.30763	2.62874	33.36363
Rank	3rd	4th	2nd	1st

Key: * indicates optimal parametric setting

In this work, the next stage is to develop the response table which is a summarized form of the signal-to-noise ratio. In summary, the frequency of occurrence of the orthogonal arrays for each parameter concerning the signal-to-noise ratio is taken into account. To demonstrate how the response table works an attempt is made to fill Table 3 by starting with the calculation of the value which would be at the intercept of level 1 and stand-off distance. To obtain this value, the concern is with the column for the stand-off distance. In the column, all entries of the orthogonal are concerned. This concern is for experimental trials 1, 2 and 3 only. It means that the orthogonal array of 1 for experimental trial 1 will be matched with the signal-to-noise ratio for that experimental trial, which is 4.9655. The orthogonal array of 1 for experimental trial 2 will also be matched with its signal-to-noise ratio of 9.6028. Thirdly, the orthogonal array 1, which represents level 1 for experimental trial 3 is matched with the signal-to-noise ratio, which is -28.6972. Now, these signal-to-noise ratios of 4.9655, 9.6028 and -28.6972 will be added and divided by 3. The value is -4.7096. It should be noted that while computing the value for the intersection of level 1 and the stand-off distance, items of an orthogonal array of two and three will not be considered. Next, the values at the intersection of level 2 and stand-off distance are computed. This is the average of -27.697, 2.5332 and 3.3763. This average is obtained as -7.259753. It is inserted at the intersection of level 2 and the stand-off distance. Now, the same procedure is conducted for the parameter called electrode gap. In this case, to obtain the value to be assigned for the intersection of level 1 and electrode gap the focus would be on experimental trials 1, 4 and 7. The average is -6.56173. Moving on to the intersection of the electrode gap and level 2, the concern is with the average of the following signal-to-noise ratio which occurred at experimental trials 2, 5 and 8. This average is -5.18397. Furthermore, the value at the intersection of the electrode gap and level 3 is computed as follows. The signal-to-noise ratios at experimental trials 3, 6 and 9 are calculated for their averages and -7.4916 was obtained. Next, this study focuses on the voltage parameter. In this case, the value at the intersection of voltage and level 1 is computed as follows. This is the average of 4.9655, 3.3763 and -27.6979, which is -6.4487. For the intersection of voltage and level 2, the following signal-to-noise ratios are calculated on an average basis, 9.6028, -27.6887 and 2.8461: The answer is -5.0799. Next, for level 3 of the voltage, the average of the following is found: -28.6972, 2.5332 and 3.0380. The result is -7.70867. Next, the parameter named medium is evaluated on its averages for the signal-to-noise ratio. For the intersection of signal-to-noise ratio and level 1, the average of the following is obtained: 4.9655, 2.5332 and 2.8461. This gives 3.4483. For level 2 of the medium, the average of the following was computed 9.6028, 3.3763 and 3.0380 to give 5.339033. By considering the intersection of level 3 and medium the average of the following is computed: -28.6972, -27.6887 and -27.6879. The average is -28.0246. The delta values along the stand-off distance are the minimum value, which is subtracted from the maximum value, i.e. (-4.70963 -(-7.26793). This gives 2.5583. By finding out the difference between the highest and the lowest for each of the parameters the electrode gap gives 2.30763. However, in ranking each parameter against one another, the principle upon which the average signal-to-noise ratio is computed is the maximization of the ratio. This means that a higher signal-to-noise ratio is desirable. If this principle is to be followed, it is worth identifying the highest delta value and assigning that one as the most desired. Based on this fact, the parameter medium with the highest delta value of 33.3636 is ranked first. The second parameter is voltage, which has a delta value of 2.6287. Next is the stand-off distance, which takes the third position. Lastly, the electrode gap occupies the fourth position. Apart from the delta value and rank, another measure of interest is the optimal parametric settings. For this problem, the optimal parametric representation for each parameter is indicated as an asterisk (*). It means that the optimal parametric setting for stand-off distance is with a value of -4.7096, which is obtained at the intersection of stand-off distance and level 1. The second component of the optimal parametric setting is the electrode gap parameter, which is -5.1840. It is obtained at level 2 of the electrode gap. For the voltage component, the optimal parametric setting is obtained at level 2 with a value of -5.0799. For the medium parameter, the optimum parametric setting is obtained at level 2 with a value of 5.3390. However, the general statement for the optimal parametric settings of the process is $SOD_1E_2V_2M_2$ where SOD, E, V and M represent the stand-off distance, electrode gap, voltage and medium respectively.

4.2. DEA application

Having applied the Taguchi method to obtain the response table for the electrohydraulic process parameter selection and optimisation problem, it is desired that the DEA is introduced for improved results. Here, all the data for the parameters within levels 1 to 3 would be used. The first stage in the application of the DEA using the CCR model is to map the various levels to the DMUs (decision-making units). Therefore, Table 4 will be used for this purpose. At this point, the application of DMU to the problem is to introduce the concept of system efficiency. The introduction of DMUs, to represent various parametric levels makes it possible for the parameters to interface. It occurs in the various thresholds of performance. In addition, it aids in gathering information about the parameters and drives towards making superior formability decisions, thereby reducing time wastage and money. To apply the principle of DEA, there is a need to classify the parameters as inputs and outputs. The inputs include stand-off distance, electrode gap, voltage and medium. However, the experimental data of (Shrivastava et al., 2019) shows the output in 9 experiments. In particular, the two types shown are the dome height in millimetres and the peak major strain in millimetres Table 4.

Table 4. Response-DMU table

	Factors (parameters)				Outputs	
DMU	SOD (mm) (Beneficial)	Electrode gap (mm) (Non-beneficial)	Voltage (Beneficial)	Medium (Beneficial)	Dome height (mm) (Beneficial)	Peak major strain (%) (Beneficial)
1	-4.70963	-6.56173	-6.4487	3.448267	1.58	2.19
2	-7.25973	-5.18397	-5.07993	5.339033	5.22	5.94
3	-7.26793	-7.4916	-7.70867	-28.0246	8.29	11.02
$\sqrt{\sum_{i=1}^{n} X_{ij}^2}$	11.30076	11.22737	11.26122	28.73628	9.92315	12.70906

But for us to do the computation properly there is a need to convert the 9 experimental datasets to 3 levels. The following is the approach used by first considering the dome height as a parameter. The data given for dome height for experiments 1 to 9 in millimetres are as follows: 5.45, 7.02, 1.90, 2.57, 7.96, 4.45, 9.90, 1.08 and 5.75. Now, the data may be arranged in ascending order as follows: 1.08, 1.90, 2.57, 4.45, 5.45, 5.75, 7.02, 7.96 and 9.9. Furthermore, it is important to create 3 different levels from the data. This means that the first three data points, which are 1.08, 1.90 and 2.57, will be added and the average will be found. This average will be the value for level 1. This value is 1.58. In the same manner, the average of data point 4 to data point 6 will be found and the value placed at level 2. This is 5.22. Similarly, data points

7 to 9 will be added and divided by 3 to obtain an average for level 3 of the dome height parameter. This gives a value of 8.29 for level 3. In the same manner, the data points for the peak major strain parameter are arranged in ascending order as 1.44, 2.40, 2.74, 5.38, 5.81, 6.63, 7.35, 12.40 and 13.32. Similarly, the averages of the data points 1, 2 and 3 will give the value for level 1 under the peak major strain parameter. The average for data points 4, 5, and 6 would give the value for level 2. The average for data points 7, 8 and 9 would give the value for level 3. Thus, for the peak major strain parameter, the values for levels 1, 2 and 3 are 2.19, 5.94 and 11.02, respectively. Based on the DMU values for both the input and output, the square root of the squares for each value of the DMU is calculated. As an example, this outcome is calculated for stand-off distance as follows. For DMU 1, the square of -4.70963 is 22.1806. For DMU 2 and 3, each of the squares is 52.7037 and 52.8228, respectively. Then the sum of the entire square is 127.707. Then the outcome needed is the square root, which is 11.3008. By using the same method, all other values are computed for both inputs and outputs. The next stage is to obtain the normalized value of each number in the cell by dividing each number by the obtained value from the square root. The new table will then be Table 5.

Table 5. Response-DMU normalized table

	Factors (parameters)				Outputs	
DMU	**SOD (mm) (Non-beneficial)**	**Electrode gap (mm) (Non-beneficial)**	**Voltage (Non-beneficial)**	**Medium (Non-beneficial)**	**Dome height (mm) (Beneficial)**	**Peak major strain (%) (Beneficial)**
1	-0.4168	-0.5844	-0.5727	0.1200	0.1592	0.1723
2	-0.6424	-0.4617	-0.4511	0.1858	0.5260	0.4674
3	-0.6431	-0.6673	-0.6845	-0.9752	0.8354	0.8671

It should be noted that after developing Table 5, which contains the integration of the response table of the Taguchi method and the decision-making unit of the DEA, linear programs are formulated in three causes g1,g2 and g3. For the first case,g1, the objective function and the contract equation are shown here:(g1), Furthermore, the details of the objective function and the constraints for the (g2)and (g3) modules are indicated as follows: (g2)(g3). But those formulations are solved using the linear programming solved name "appspot." Now, the results of naming the linear programmers on "appspot" are indicated below in the summary while the full details are in the appendix.

Case 1: In this case, the solution obtained in terms of the efficiency of the inputs and the generation of the outputs at optimum results are stand-off distance = 0.1466, electrode gap= 0, voltage= 0.0269, medium= 0.7342. However, the dome height yields 0.7317 while the peak major strain yields 0.7594.

Case 2: For the case 2 results, the stand-off distance= 1.0874, electrode gap= 0, voltage= 0.6268, medium= 0.8606. Nonetheless, the dome height gives 0.5781 while the peak major strain gives 0.6000.

Case 3: For case 3, the stand-off distance =1.2745, electrode gap = 0, voltage = 0, medium = 0. However, the dome height =0.8354 while the peak major strain yields 0.8671.

From the above results of the linear programming formulation, in case 1, the most efficient input is the medium, which exhibits an efficiency of 0.7342 while the electrode gap is the worst input parameter that is not efficient at all. On the side of the outputs, at optimal points, the major peak strain shows superior performance at 0.7594 but the dome height performed less at 0.7317. This means that additional investigations of the causal factors for the lower performance of the dome height need to be conducted to improve its performance. Also, given the scarce resources in the electrohydraulic process, more resources should be directed to the peak major strain output to further improve it. Now, case 2 is considered where the most efficient input is identified as stand-off distance with an outstanding value of 1.0874, which means that is working at 100% efficiency. But the worst input is the electrode gap with an efficiency value of 0. It means that concerted efforts should be made on how to improve the efficiency of the electrode gap. For the outputs, the peak major strain, performing at 0.6000 during optimality outweighs the performance of the dome height. For case 3, the most efficient input parameter is the stand-off distance at 1.2745, which indicates 100% efficiency since it is over 1. Notwithstanding, the worst parameters are electrode gap, voltage and medium as they record 0 efficiency. On the side of the outputs, the peak major strain performs better than the dome height. Overall, stand-off distance is the best parameter followed by the medium**.** Furthermore, regarding outputs, the best in terms of optimal results is the peak major strain while the dome height is the worst output.

4.3. Integrating DEA and Pareto

Having obtained the efficiency value of the parameters and with the knowledge of the response table, the weight of the DEA will now be used to multiply the translated orthogonal array and the S/N ratio will be recalculated. Table 6 shows the weight obtained from the efficiency calculation. The modified translated orthogonal array is calculated as per the result obtained from the product of the weight and the value of the translated stand-off distance by considering each of the experimental trials. Consider experimental trial 1 which has the value of 10, 20, 220 and 0.894, for the stand-off distance, electrode gap, voltage and medium respectively, with the product of the weight. For stand-off distance, consider 0.1466 as the weight and 10 for the previous value of the stand-off distance and experimental trial 1 intersection, the new value to be placed at the intersection is 1.4658 Table 6.

Table 6. Parameter-weight value for the computation of modified signal-to-noise ratios (Case 1)

Orthogonal array					Modified translated orthogonal array				
				Weights→	**0.1466**	**0**	**0.0269**	**0.7342**	
Sr. No.	SOD (mm)	Electrode gap (mm)	Voltage	Medium	SOD (mm)	Electrode gap (mm)	Voltage	Medium	SNR
1	1	1	1	1	1.4658	0.0000	5.9126	0.6535	0.2443
2	1	2	2	2	1.4658	0.0000	6.9876	1.1234	3.7047
3	1	3	3	3	1.4658	0.0000	8.0626	0.0135	-32.6304
4	2	1	2	3	2.9315	0.0000	6.9876	0.0135	-32.6301
5	2	2	3	1	2.9315	0.0000	8.0626	0.6535	0.8379
6	2	3	1	2	2.9315	0.0000	5.9126	1.1234	5.0520
7	3	1	3	2	4.3973	0.0000	8.0626	1.1234	5.4286
8	3	2	1	3	4.3973	0.0000	5.9126	0.0135	-32.6301
9	3	3	2	1	4.3973	0.0000	6.9876	0.6535	0.9437

Next, under the electrode gap, the value of the weight is 0 while the translated value is 20. Finding their product, the value of 0 is returned to the intersection between electrode and experimental trial 1. For the intersection of the voltage and experimental trial 1 the product of 220 and 0.0268754 is obtained as 5.912588. Under the intersection of medium and experimental trial 1, the product of 0.7342264 and 0.89 is found as 0.653461. Having obtained the newly modified translated orthogonal values the next task is to compute the signal-to-noise ratio which was calculated based on the higher the better signal-to-noise ratio criterion. Applying the formula for this (equation 1), a value of 0.2443 was obtained. The same procedure that was used for experimental trial 1 will now be used for other experimental trials up to trial 9. This gives us a range of values for the signal-to-noise ratio from -32.6304 to 5.4286. Furthermore, the percentage contribution of the signal-to-noise ratio for each experimental trial is calculated. This gives the least contribution as experimental trial 1 with a percentage of 0.2141% while the highest contribution comes from experimental trial 3 with 28.5976%. Besides, the percentage cumulative of the signal-to-noise ratio is computed where the percentage representing the first experimental trial is the starting value for the percentage cumulative column to obtain the value for experimental trial 2. The actual contribution percentage is added to that of the percentage contribution of experimental trial 1, which is 0.241% plus 3.2468% which gives 3.4609%. Subsequent computations are done in this order. Now, to apply the Pareto scheme the percentage cumulative that is close to 80% is observed. In this case, the closest experiment trial is experimental trial 7.

Table 7. Absolute and cumulative percentage computations for cases 1 to 3

	Case 1			Case 2			Case 3		
Exp. No.	**Absolute SNR**	**% Change**	**Cumulative %**	**Absolute SNR**	**% Change**	**Cumulative %**	**Absolute SNR**	**% Change**	**Cumulative %**
1	0.2443	0.2141	0.2141	2.4337	1.9870	1.9870	26.8783	9.3135	9.3135
2	3.7047	3.2468	3.4609	7.0979	5.7949	7.7819	26.8783	9.3135	18.6271
3	32.6304	28.5976	32.0585	31.2503	25.5137	33.2956	26.8783	9.3135	27.9406
4	32.6301	28.5974	60.6559	31.2503	25.5137	58.8092	32.8989	11.3997	39.3404
5	0.8379	0.73436	61.3902	2.4500	2.0002	60.8094	32.8989	11.3997	50.7401
6	5.0520	4.4276	65.81786	7.1451	5.8335	66.6429	32.8989	11.3997	62.1398
7	5.4286	4.7577	70.5756	7.1541	5.8408	72.4837	36.4207	12.6201	74.7599
8	32.6301	28.5973	99.1729	31.2503	25.5137	97.9974	36.4207	12.6201	87.3799
9	0.9437	0.8271	100	2.4529	2.0026	100	36.4207	12.6201	100
Sum	114.10181			122.4844			288.5936		

Table 8. Parameter-weight value for the computation of modified signal-to-noise ratios (Case 1)- Pareto scheme

Orthogonal array					Modified translated orthogonal array				
				Weights →	**0.14658**	**0**	**0.02688**	**0.7342**	
Sr. No.	**SOD (mm)**	**Electrode gap (mm)**	**Voltage**	**Medium**	**SOD (mm)**	**Electrode gap (mm)**	**Voltage**	**Medium**	**SNR**
1	1	1	1	1	1.4658	0.0000	5.9126	0.6535	0.2443
2	1	2	2	2	1.4658	0.0000	6.9876	1.1234	3.7047
3	1	3	3	3	1.4658	0.0000	8.0626	0.0135	-32.6304
4	2	1	2	3	2.9315	0.0000	6.9876	0.0135	-32.6301
5	2	2	3	1	2.9315	0.0000	8.0626	0.6535	0.8379
6	2	3	1	2	2.9315	0.0000	5.9126	1.1234	5.0520
7	3	1	3	2	4.3973	0.0000	8.0626	1.1234	5.4286

By looking at the percentage cumulative for case 1 it was observed that experimental trial 7 has 70.0758% and experimental trial 8 has 99.1729%. However, based on the Pareto principle 80% is our target. By considering the distance of each of the percentage cumulative for experimental trial 7 and experimental trial 8 (Table 7), experimental trial 7 is closer by roughly 9.95%. Furthermore, experimental trial 8 is away from 80% by roughly 19%, therefore experimental trial 7 is regarded as the cut-off for case 1, by using the same argument experimental trial 7 remains the cut-off for case 2 with a value of 72.4837%.

Table 9. Response table- Pareto (Case 1)

	Factors (parameters)			
Level	SOD (mm)	Electrode gap (mm)	Voltage	Medium
1	-9.56047	-8.98573	2.64815*	0.5411
2	-10.5974	2.2713*	-14.4627	4.728433*
3	5.4286*	-13.7892	-8.78797	-32.6303
Delta	16.026	16.0605	17.11085	37.358733
Rank	4th	3rd	2nd	1st

Key: * indicates optimal parametric setting

For case 3, it is also experimental trial 7 which is the closest to 80%. In all, experimental trials 8 and 9 are discarded in the new set of computations for the modified. Signal-to-noise ratio computation. Moreover, the aim is to calculate the delta value, rank and optimal parametric values of the newly modified structure, to achieve this Table 8 is developed in which all entries of experimental trials 8 and 9 are discarded. Moving forward, Table 9 is created for the response table at the application of the Pareto scheme. The question relates to how to fill the response table operator in Table 9. To do this, the interaction of stand-off distance and level 1 is the commencement point. Here, the average of 0.2443,3.7047 and -32.6304 representing the signal-to-noise ratio for level 1 associated with stand-off distance is found this value, obtained as -9.56047, is placed at the intersection of the stand-off distance and level 1. To obtain the value at the intersection of stand-off distance and level 2 the average of -32.6301, 0.8379 and 5.5020 is found. These represent the signal-to-noise ratio of experimental trials 4,5 and 6 the value obtained is -10.5974. At the intersection of stand-off distance and level 3 only experiment 7 is considered the value obtained is 5.4286. Next, the value at the intersection of the electrode gap and level 1 is computed. This concerns the experimental trials 1, 4, and 7 while the average is -8.9857. For the intersection of the electrode gap and level 2, the average of 3.7047 and 0.8379 representing the signal-to-noise ratio for experimental trials 2 and 5 is found to be 2.2713. Next, the values at the intersection of the electrode gap and level 3 are -32.6304 and 5.0520 which are for experimental trials 3 and 6. It gives a value of -14.7892. Next, the value for the intersection of voltage and level 1 is computed. This is obtained as the average of 0.2443 and 5.0520 which are for experimental trials 1 and 6 this gives 2.6482. For the intersection of voltage and level 2, an average of 3.7074 and 32.6301 is found. These are for experimental trials 2 and 4. It gives a value of -14.4627 next the intersection of voltage and level 3 is computed based on the average of -32.6304, 0.8379 and 5.4286. The associated experimental trials are 3, 5 and 7 and the average is -8.78797. Finally, the values at the intersection of medium and level 1, 2and 3 are computed, which give 0.5411, 4.7284 and -32.6303, respectively. Having obtained all the values of the parameter at all levels the optimal parametric setting is $SOD_{3,}E_2V_2M_2$. The performance characteristics in the electrohydraulic forming process can be effectively improved at optimal threshold values. The EHF process has the characteristics of a stand-off distance of 3mm, an electrode gap of 30mm a voltage of 260 volts and the medium as Oil with a viscosity of 0.89cP for case 1, having an optimal parametric setting of $SOD_3E_2V_2M_2$. The delta values are 16.026, 16.0605, 17.11085 and 37.3587. Based on the Pareto intervention, the medium is ranked first while voltage, electrode gap and stand-off distance are ranked second, third and fourth, respectively. The above values are for case 1 alone. Thus, this is the result produced by the Taguchi-DEA-Pareto method applied to the EHF process. In comparison with the result of Taguchi alone, there is a consistency of ranking in 50% of the parameters while the other 50% of the parameters are ranked differently. For instance, comparing Table 3 and Table 9, medium and voltage are ranked as first and second respectively, in both tables whereas electrode and stand-off distance are ranked differently also. The delta values show higher variability in the Pareto scheme than in the Taguchi scheme alone.

Table 10. Response table – Case 2

	Factors (parameters)			
Level	**SOD (mm)**	**Electrode gap (mm)**	**Voltage**	**Medium**
1	-8.53276	-8.52096	3.492526	1.143109
2	-8.51951	3.482871*	-13.3681	5.839167*
3	5.852925*	-13.3534	5.852925*	-32.5538
Delta	14.38568	16.83625	19.22106	38.39297
Rank	4th	3rd	2nd	1st

Key: * indicates optimal parametric setting

Table 11. Response table – Case 3

	Factors (parameters)			
Level	**SOD (mm)**	**Electrode gap (mm)**	**Voltage**	**Medium**
1	26.87828	32.0659567*	29.88858	29.88858
2	32.89888*	29.88858	29.88858	32.0659567*
3	26.87828	29.88858	32.0659567*	29.88858
Delta	6.0206	2.1774	2.1774	2.1774
Rank	1st	2nd	2nd	2nd

Key: * indicates optimal parametric setting

The above was made in case 1, however, case 2 may be different. Thus, in implementing case 2, the starting point is when the weight is obtained from the decision-making unit of the DEA method. The weights of stand-off distance, electrode gap, voltage and medium are 1.0874, 0, 0.6268 and 0.8606, respectively. These weights are introduced into the parameter-weight portion of the table to compute the modified signal-to-noise ratios. Now, the procedure has been fully explained for case 1 and may not be repeated here for conciseness. However, the final results for the modified signal-to-noise ratio indicated here are 1.1380, 5.8175, -32.5538, -32.5538, 1.1482, 5.8471, 5.8293, -32.5538 and 1.1500 for experimental trials 1 to 9, respectively. From this point, it is necessary to calculate the percentage cumulative along the experimental trials 1 to 9, respectively, as 0.96%, 5.86%, 33.31%, 60.75%, 61.72%, 71.59%, 99.03% and 100%. From this information, experimental trial 7 with 71.59% is chosen as the cut-off point with a value of 71.59. Therefore, for the Pareto method experimental trials 8 and 9 are discarded from further analysis. Now, the modified signal-to-noise ratio having experimental trials 1 to 7 is revisited to compute the modified response table. In doing this, the stand-off distance for levels 1, 2 and 3 are computed. These are given as -8.5328, -8.5195 and 5.8529. Other values for levels 1 to 3 for electrode gap voltage and medium are shown in Table 10. However, based on the delta values computed, the ranks obtained in Table 10 compared with that of Table 9 show no difference. However, from a further comparison of Table 10 with Table 3, it is shown that medium and voltage ranked first and second, respectively, but the positions of electrode gap and stand-off distance are different. The optimal parametric setting for case 2 is $SOD_3E_2V_3M_2$. For case 2 with an optimal parametric setting of $SOD_3E_2V_3M_2$, the meaning is as follows: The need characteristics of the system include a stand-off distance of 30mm, an electrode gap of 30mm, a voltage of 300 volts and oil of viscosity at 0.89cP as a medium. Now, moving to case 3, the weight generated from the decision-making unit is multiplied by the translated value of the orthogonal array to yield 12.7454, 12.7454, 12.7454, 25.4908, 25.4908, 25.4908, 38.3292, 38.3292, 38.3292 for experimental trials 1 to 9, respectively, for standoff distance. However, for all other values for parameters, namely, electrode gap, voltage and medium, the values for experimental trials 1 to 9 are all zero. It is interesting to obtain the signal-to-noise ratio with the new data. A further computation is to obtain the percentage cumulative for all the experimental trials which, obtained for experimental trials 1 to 9 are 9.32, 18.63, 27.94, 39.34, 50.74, 62.14, 74.76, 87.38 and 100, respectively. Now, from this data, the cut-off of 80% makes experimental trials 1 to 7 relevant. Therefore, experimental trials 8 and 9 are discarded while the parametric settings, delta values and rank are determined for case 3. In case 3, the optimal parametric setting is $SOD_2E_1V_3M_2$. Moreover, case 3 is interpreted as a stand-off distance of 20mm, an electrode gap of 20mm, a voltage of 220 volts and oil at a viscosity of 0.89cP as the medium of the system. The delta values are 6.0206, 2.1774, 2.1774 and 2.1774. However, the ranks and stand-off distance were in the first position while there is a tie among electrode gap, voltage and medium, which gives them the second position.

4.4. Implications and limitations of the study

This study explored the crucial question of how the optimisation performance of aluminium alloy 1100sheets for automotive panels may be assessed and ranked in an electrohydraulic forming process. However, the major finding revealed that (from the averages of efficiency values of different cases) stand-off distance, electrode gap, voltage, and medium have efficiency indices of 0.8362, 0, 0.2179 and 0.5316, respectively. This detailed analysis provides an absolute understanding of the operational procedures relating to efficient machining operations in the system. Standoff distance is found to be the most efficient while electrode gap is the least efficient design variable. Consequently, a very likely cause of the inefficiency is the lack or poor quality communication of the characteristics of the electrode gap in the electrohydraulic forming process. Thus, operators, engineers and managers should communicate effectively on the electrode gap to remove this constraint. To overcome this problem, the management should be organization training to improve the existing communication culture of the operators and engineers. This highlights also the pivotal role that technology plays in the context of forming operations. Thus training could be done via video conferencing or some other means which will be done at the convenience of the workers while pursuing productivity. In sum, the management can foster improvement in the efficiency values and ranks of the electrode gap by ensuring the feedback on the training programme and implemented for correctional purposes.

Moreover, this study presents significant understanding and also shows limitations that suggest areas for future investigations. First, this study is limited to the integration of three methods, namely Taguchi, DEA and Pareto. In the future, some interesting aspects of the replacement of the DEA method with multicriteria methods such as MOORA should be attempted. Expanding this study to compare with other aluminium alloys such as aluminium (AA3003, AA3004 and AA3105) could offer valuable comparative insights.

5. CONCLUSIONS

In this work, a new method is presented where the response table information, which represents the Taguchi method, is integrated with the DEA method and further joined with the Pareto method. The method used, named as T-DEA-P method, combines the characteristics of the three methods of Taguchi, DEA and Pareto. Firstly, it showed the optimal parametric settings of the Taguchi method. Secondly, it displays the efficiency of the parameters while conceptualizing the level as a decision-making unit. Thirdly, it applies the Pareto scheme to discriminate the experimental trials. In all, the optimal parametric settings, ranks and delta values were obtained for both the final and intermediate levels. In case 1, the parameters called medium and voltage were classified as the best and second best, respectively, while electrode gap and stand-off distance were found as poor-performing parameters. The result of case 1 is similar to the initial one before applying the Pareto method. In case 2, a similar result was also obtained to compare with case one and the result with applying Pareto. However, case 3 gives a different result where the first parameter is the stand-off distance while other parameters are classified as second. Given the results obtained, any of cases 1 and 2 could be used for implementation purposes.

The principal results of the article are in the following aspects: (1) it proposed an optimisation efficiency decision method for the EHF process using the aluminium (AA1100) sheets for automotive panels. The results of the signal-to-noise ratios are analyzed under different conditions to establish the optimal parametric settings, delta values and the ranks of the four principal parameters used in the model. The parameters are the stand-off distance, electrode gap, voltage and medium. By considering these details, the following are relevant:

Situation 0: This is when the signal-to-noise ratios are drawn from the translated orthogonal array. The signal-to-noise ratios (SNRs) are interpreted from the individual orthogonal array element based on the high-the-better criterion. All nine experimental trials are accounted for in the SNR computation. The average is then obtained as the response table from which the optimal parametric settings, delta values and ranks are obtained.

Situation 1 (Case 1): The modified translated orthogonal array forms the basis for analyzing the SNRs. Here, the efficiency values of the parameters are introduced as weights where the standoff distance, electrode gap, voltage and medium assume efficiency values of 0.1466, 0, 0.0269 and 0.7342, respectively. The interpretation of SNR is made according to the higher-the-better criterion. Based on Pareto's cut-off principle, a percentage accumulative of 70.58% is only allowed for the further computation of the optimal parametric setting, delta value and rank evaluations. Thus, experimental trials 8 and 9 are discarded.

Situation 2 (Case 2): Evaluations are based on the modified translated orthogonal arrays where the SNRs are computed based on new values that are different from in situations 0 and 1. The introduction of the efficiency values for the parametric weights, which are needed to generate new optimal parametric settings, ranks and delta values are made. The values of 1.0874, 0, 0.6268 and 0.8606 are the efficiency of the standoff distance, electrode gap, voltage and medium, respectively. To introduce the Pareto scheme principle, an 80% cut-off is observed, which picks 72.48% of the percentage cumulative and drops off the experimental trial and 9. Then the optimal parametric setting, delta values and ranks of the parameters are determined.

Situation 3 (Case 3): Here, the modified translated orthogonal array is deployed to analyse the SNRs. The efficiency indices for the parameters used are 1.2745, 0, 0 and 0 for standoff distance electrode gap voltage and medium, respectively. These efficiency indices are integrated with the modified orthogonal array to yield the SNRs. The cutoff point according to the Pareto scheme is 74.76%. At this point, experimental trials 8 and 9 are discarded while the computation of the optimal parametric setting, delta values and ranks is made.

In this work, the issue of performance optimisation and ranking of parameters during the processing of aluminium alloy 1100 sheets was addressed. This issue is significant as most electrohydraulic forming processes continue to waste resources that could have been prudently saved by being aware of the parametric thresholds in the process. The importance of this problem is found in the continuously difficult manufacturing environment, which requires more efficiency to survive. Therefore, this study provides valuable insights and impacts on the economy of the forming process. Consequently, the cumulative effect of implementing the proposed approach is a sound decision-making process, which will enhance sustainable practice in the forming industry.

List of abbreviations

T-DEA-P	Taguchi-Data envelopment analysis-Pareto method
SOD	Stand-off distance
E	Electrode gap
V	Voltage
M	Medium
SNR	Signal-to-noise ratio
AA1100	Aluminium alloy class 1100
EHF	Electrohydraulic forming
DEA	Data envelopment analysis

6. REFERENCES

Ahmed M., Kumar D.R. & Nabi M. 2017, 'Enhancement of formability of AA5052 alloy sheets by electrohydraulic forming process,' Journal of Materials Engineering and Performance, 26:439–452. https://doi.org/10.1007/s11665-016-2446-0

Ahmed M., Shrivastava A., Ravikumar D. & Nabi M.U. 2020, 'Optimisation of process parameters for energy-efficient electro-hydraulic forming of Al-Mg alloy sheets,' Advances in Materials and Processing Technologies, 6(3): 620-636. https://doi.org/10.1080/2374068X.2020.1731228

Avrillaud G., Mazars, G., Cantergiani, E., Beguet, F., Cuq-Lelandais, J.-P., Deroy, J. 2021, 'Examples of how increased formability through high strain rates can be used in electro-hydraulic forming and electromagnetic forming industrial applications,' Journal of Manufacturing and Materials Processing, 5, Article 96. https://doi.org/10.3390/jmmp5030096

Ayaz M., Khaki D., Arab N. & Noroozi, A. 2013, 'Optimisation of the hot rolling parameters for evaluation of the formability of Nb-micro alloyed steel sheet by using the Taguchi method.

International Journal of Materials Research, l104(12): 1212-1222. https://doi.org/10.3139/146.110973

Balasundar I. 2013, 'Optimisation of process parameters to maximize formability for better productivity by using Taguchi method,' International Journal of Mechanical Engineering, 5:63-67

Bonnen J.J.F., Golovashchenko S.F., Dawson S.A. 2012, 'Electrode erosion observed in electrohydraulic discharges used in pulsed sheet metal forming,' Journal of Materials Engineering and Performance, 22: 3946–3958. https://doi.org/10.1007/978-3-319-48179-1_76

Bonnen J.J.F., Golovashchenko S.F., Dawson S.A. 2013, 'Electrode erosion observed in electrohydraulic discharges used in pulsed sheet metal forming,' Journal of Materials Engineering and Performance, 22:3946–3958. https://doi.org/10.1007/s11665-013-0690-0

Budiono H.D.S., Nurcahyo R., Habiburrahman M. 2021, 'Relationship between manufacturing complexity, strategy, and performance of manufacturing industries in Indonesia,' Heliyon, 7(6), e07225. https://doi.org/10.1016/j.heliyon.2021.e07225

Cai D., Liang J., Ou H., Li G., & Cui J. 2021, 'Mechanical properties and joining mechanism of electrohydraulic expansion joints for 6063 aluminium alloy/304 stainless steel thin-walled pipes,' Thin-Walled Structures, 161, Article 107427. https://doi.org/10.1016/j.tws.2020.107427

Dai K., Zhu Z., Shen G., Tang Y., Li X., Wang W., & Wang Q. 2022, 'Adaptive force tracking control of electrohydraulic systems with low load using the modified LuGre friction model,' Control Engineering Practice, 125, Article 105213. https://doi.org/10.1016/j.conengprac.2022.105213

Elangovan K., & Narayanan C.S. 2010, 'Application of Taguchi approach on investigation of formability for perforated Al 8011 sheets,' International Journal of Engineering Science and Technology, 2: 300-309

Grynia D., Kadziński M., Stamenković M. 2024, 'Attaining robust performance targets in data envelopment analysis with application to efficiency evaluation of airports,' Computers & Industrial Engineering, 190, Article 110065.

Holzmüller M., Linnemann M., Homberg W., Psyk V., Kräusel V., Kroos J. 2023, 'Proof of concept for incremental sheet metal forming by means of electromagnetic and electrohydraulic high-speed forming,’ Materials Research Proceedings, 25:11-18. https://doi.org/10.21741/9781644902417-2

Homberg W., Beerwald C. & Pröbsting A. 2010, ‘Investigation of the electrohydraulic forming process with respect to the design of sharp edged contours,’ 4th International Conference on High Speed Forming, March 9th-10th 2010 Columbus, Ohio, USA. https://doi.org/10.17877/DE290R-8737

Homberg W., Djakow E., &Damerow O. 2014, ‘Process reliability and reproducibility of pneumomechanical and electrohydraulic forming processes,’ International Conference on High Speed Forming, Daejeon

https://doi.org/10.1016/j.cie.2024.110065

Hvam L., Hansen C.L., Forza C., Mortensen N.H. & Haug A. 2020, ‘The reduction of product and process complexity based on the quantification of product complexity costs,’ International Journal of Production Research, 58(2): 350-366. https://doi.org/10.1080/00207543.2019.1587188

Jenab A., Green D., Alpas A. T., & Boyle K. 2015, ‘Formability of AA5182-0 sheet during electro-hydraulic forming: influence of input energy. In Materials Science and Technology 2015 Conference, Columbus, Ohio, USA.

Kosenkov V.M., Bychkov V.M. 2019, ‘Influence of some axially symmetric stepped forms of discharge chambers on the efficiency of electrohydraulic forming,’ Surface Engineering and Applied Electrochemistry, 55, 89–96 https://doi.org/10.3103/S1068375519010113

Lakshmi A. A., Ch S.R., Sateesh N. & Subbiah R. 2022, ‘Implementation of taguchi approach on investigation of formability for Al 8011 sheets at elevated temperatures,’ Advances in Materials and Processing Technologies, 8:619-634, https://doi.org/10.1080/2374068X.2021.1945312

Li S., Yan Y., Jiang D., & Guo Q. 2023, ‘Synchronized control of multiple electrohydraulic systems with terminal sliding mode observer under parametric uncertainty and external load. ISA Transactions,’ 133: 475-484. https://doi.org/10.1016/j.isatra.2022.06.044

Modi B. and Kumar D.R. 2019. Optimisation of process parameters to enhance formability of AA 5182 alloy in deep drawing of square cups by hydroforming, Journal of Mechanical Science and Technology, Vol. 33, pp. 5337–5346 https://doi.org/10.1007/s12206-019-1026-2

Natarajan H., Paramasivam S.S., Kumaran D., Krishnan G.S., Ibrahim S.S. 2021, ‘Application of MABAC in support of decision-making on the key process variables in sheet metal forming,’ Materials Today: Proceedings, 47(19):7140-7144. https://doi.org/10.1016/j.matpr.2021.06.309

Oji B.C. and Oke S.A. 2020, ‘Optimisation of bottling process using “hard” total quality management elements,’ The TQM Journal, 33(2):473-502. https://doi.org/10.1108/TQM-03-2020-0057

Panwar G., Khanduja D. & Upadhyay V. 2024, ‘Impact of processing variables on formability of AA7079 sheet by SPIF technique,’ Journal of The Institution of Engineers (India): Series D., 105: 89–96. https://doi.org/10.1007/s40033-023-00450-5

Pérez I., Knyazyev M.K. & San José J. 2019, ‘Experimental investigation of electric discharge parameters in correlation with peak pressure at industrial electrohydraulic forming,’ SN Applied Sciences, 1, Article 1299. https://doi.org/10.1007/s42452-019-1336-0

Sarraf I., & Green D. 2018, ‘Simulation of electrohydraulic free forming of DP600 sheets using a modified Rousselier damage model,’ Journal of Physics Conference Series, 1063(1), 012111. https://doi.org/10.1088/1742-6596/1063/1/012111

Shrivastava A., Ahmed M., Ravikumar D. 2019, ‘Optimisation of process parameters in electrohydraulic forming using Taguchi method,’ ISME Journal of Manufacturing Sciences, 8(1): 7-15

Wang Z., Lai Z., Han X & Li L. 2023, ‘Antisymmetric deformation behavior during eccentric explosion electro-hydraulic sheet forming process,’ Materials and Manufacturing Processes, 38(6):692-700. https://doi.org/10.1080/10426914.2022.2116041

Wei Y. N., Zhang F., Wei B., & Xu H. 2021, ‘Experimental and numerical analyses of tubular electrohydraulic forming process,’ Key Engineering Materials, 871: 80-86. https://doi.org/10.4028/www.scientific.net/KEM.871.80

Wu Y., Li K., Fu X. 2024, ‘An integrated zero-sum game and data envelopment analysis model for efficiency analysis and regional carbon emission allocation,’ Decision Analytics, 10, Article 100387. https://doi.org/10.1016/j.dajour.2023.100387

Yu H., Sun L., Zhang X., & Wang S. 2017, ‘Experiments on electrohydraulic forming and electromagnetic forming of aluminium tube,’ The International Journal of Advanced Manufacturing Technology, 89:1-8. https://doi.org/10.1007/s00170-016-9261-5

Zavari S., Bakhshi-J. M. & Gorji H. 2020, 'Combined electrohydraulic and flexible pin die forming: a novel high strain rate forming die setup,' International Journal Advanced Manufacturing Technology, 111(7-8):1-17. https://doi.org/10.1007/s00170-020-06242-5

Zhang F., Wei Y., He K., & Hang Z. 2020, 'Experimental investigation on electro-hydraulic forming with flexible-die,' Procedia Manufacturing, 50, 324-327. https://doi.org/10.1016/j.promfg.2020.08.060

Zhang H., Liu K., Li J., Zhang K., Ou Y., Lu Z., Shi J., Cai Z., & Chen Y. 2023, 'Experimental study on stepped discharge modes of cyclic electrohydraulic shockwaves,' Geoenergy Science and Engineering, 227, 211871. https://doi.org/10.1016/j.geoen.2023.211871

Zhang Y., Li X ., Tang Y ., Liu H ., Ouyang S., Zhang Z., Cao Q., Li L. 2022, 'Research into controlling the material flow for electrohydraulic forming alloy tubes by a pulsed magnet,' IEEE Transactions on Applied Superconductivity, 32(6): 1-5. https://doi.org/10.1109/TASC.2022.3149859

Zheng Q., Yu H. 2021, 'Influence of scaleboard on the dispersion deformation behaviour of DP600 steel sheets during electrohydraulic forming,' The International Journal of Advanced Manufacturing Technology, 114: 757–769. https://doi.org/10.1007/s00170-021-06904-y

Zohoor, M., Mousavi, S.M. 2018, 'Evaluation and optimisation of effective parameters in electrohydraulic forming process,' Journal of the Brazilian Society of Mechanical Sciences and Engineering, 40, Article 524. https://doi.org/10.1007/s40430-018-1449-1.

Appendix

Case 1 : var a >= 0; var b >= 0; var c >= 0; var d >= 0; var e >= 0; var f >= 0;
minimize z: - 0.4167c - 0.5844d - 0.57265e - 0.1199f;
subject to c11: 0.159224a +0.172318b+ 0.41675c+ 0.5844d + 0.57265e - 0.1199f <= 0;
subject to c12: 0.526643a +0.467383b + 0.6421c +0.46173d + 0.4511e - 0.185794f <= 0;
subject to c13: 0.83542a +0.867098b + 0.64314c + 0.66726d + 0.68453e + 0.97523f <= 0;
end;
A = 0.731678, B = 0.759422, C = 0.1465752, D = 0, E = 0.0268754, F = 0.7342264

Case 2: var a >= 0; var b >= 0; var c >= 0; var d >= 0; var e >= 0; var f >= 0;
minimize z: 0.64241c - 0.46173d - 0.411e + 0.185794f;
subject to c11: 0.159224a +0.172318b+ 0.41675c+ 0.5844d + 0.57265e - 0.1199f <= 0;
subject to c12: 0.526643a +0.467383b + 0.6421c +0.46173d + 0.4511e - 0.185794f <= 0;
subject to c13: 0.83542a +0.867098b + 0.64314c + 0.66726d + 0.68453e + 0.97523f <= 0;
end;
A= 0.5780932, B = 0.6000137, C = 1.0874495, D = 0, E = 0..626805, F = 0.8606328

Case 3: var a >= 0; var b >= 0; var c >= 0; var d >= 0; var e >= 0; var f >= 0;

minimize z: 0.6314*c - 0.66726d - 0.68453e -0.97523*f;
subject to c11: 0.159224a +0.172318b+ 0.41675c+ 0.5844d + 0.57265e - 0.1199f <= 0;
subject to c12: 0.526643a +0.467383b + 0.6421c +0.46173d + 0.4511e - 0.185794f <= 0;
subject to c13: 0.83542a +0.867098b + 0.64314c + 0.66726d + 0.68453e + 0.97523f <= 0;
end;
A = 0.83542, B = 0.867098, C = 1.27454, D = 0, E = 0, F = 0